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FoM to Compare the Effect of ASK Based Communications on Remotely Powered Systems

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***Abstract*—This paper presents a Figure-of-Merit to compare the remotely powered communication systems. The important parameters for remote powering and also communication are presented. The effect of ASK based communications on remote powering performance is analyzed by representing the challenges of power transfer during data transmission. This Figure-of-Merit is introduced to compare different modulation types in terms of powering and communication performances.**

I. Introduction

In remotely powered systems, the power transmission is difficult due to the low coupling between the reader and the tag. The power transmission during communication becomes even more challenging in case the power and the data are usually transmitted via the same frequency.

In this paper a Figure-of-Merit (FoM) is proposed to compare the performances of different remotely powered communication systems. Although it is applicable to UHF-RFID tags, the main consideration in this paper is to introduce the FoM by analyzing the inductively coupled systems.

The proposed FoM is a function of remote powering and communication variables which can be represented by $FoM = k_{power} \cdot k_{com}$. Therefore, these factors can be analyzed in two parts; first part consists of powering issues such as the power consumption of remotely powered systems, and the link parameters and second part includes the communication parameters.

II. Remote Powering

A. Power Consumption

Remotely powered systems face several challenges. The coupling of the antennas is considerably weak due to the distance between them. Hence, the power transfer efficiency is limited so the available power at the tag is quite low for a certain reader output power. Moreover, the remotely powered systems do not usually have a battery. The batteries increase the total size and weight of the system. In addition, the battery needs to be replaced at the end of its lifetime, which means that in case of biomedical implants, a medical surgery is required to change the battery.

In a batteryless remotely powered system, the energy is supplied usually by a capacitor when the input power is insufficient. Since, the value of the capacitor is limited. The duration to maintain necessary supply is extremely low to continue the operations at the tag side without sufficient input power. Therefore, the overall power consumption of the system is a significant issue in remotely powered systems. A low-power system is essential due to the aforementioned issues.

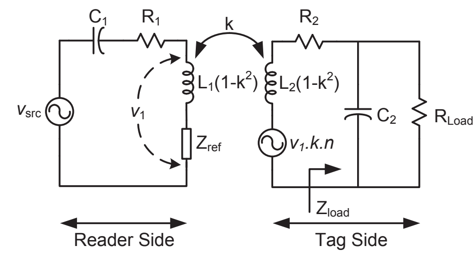


Fig. 1. Equivalent circuit of magnetically coupled power link

B. Link Parameters (Q, k, f_o)

In remotely powered systems, the power can be generally transferred by two methods. In the first method, the power is carried over by generated magnetic field. In the other method, the electromagnetic waves are used to harvest the power. Fig. 1 shows a magnetically coupled remote power link [1]. In these systems, there are two coils close to each other to increase the coupling factor. The reader coil is driven by an amplifier and generates magnetic field. At the tag side, the current induced by this magnetic field is used as the supply for the remote system.

In Fig. 1, L_1 and R_1, L_2 and R_2 are the self-inductances and the series resistances of the reader and the tag coils, respectively. R_{Load}, and v_{src} represent the load resistance and the voltage source to drive the reader coil. Moreover, C_1 and C_2 are the tuning capacitances which are used to tune the inductances to the operation frequency. The mutual inductance between the coils is represented by the coupling factor (k). Furthermore, Z_{ref}, v_1, and n are the reflected impedance of tag side to the reader side, the voltage across the inductance and the reflected impedance, and the square root of the inductances ratio ($\sqrt{L_2/L_1}$), respectively.

As seen from Fig. 1, the induced voltage at the tag side is a function of v_1, k and n parameters. Therefore, the coupling factor of the inductances has significant effect on power transmission. In addition, the quality factors of inductances (Q) are also important as the coupling factor to improve the efficiency of the link. In order to get maximum power transfer efficiency from the link, not only the coupling factor but also the quality factors of the coils should be maximized [1].

The power transfer efficiency is also affected by the operation frequency of the inductive link [2]. Consequently, as the quality factors increase with the frequency, the efficiency also increases. However, this situation holds up to a certain frequency where the parasitic effects of the coil become dominant [3]. Additionally, the power consumption of the auxiliary circuits increase with frequency, which decreases the overall power transfer efficiency.

III. Communication

The communication circuits such as VCOs and PAs are usually the most power hungry parts in a transceiver. Therefore, using a second channel for data communication which requires VCO and PA circuits is not preferable in order not to increase the overall power consumption of the system. In addition, using another channel needs extra antenna or coil which increase also the total size of the system. Accordingly, the remotely powered systems mostly use the same frequency for remote powering and also data communication for both directions.

A. Modulation Methods

The communication method depends drastically on the application. Some applications such as stimulation of the nerves require high data rates to send commands from the reader to the tag. On the other hand, some applications such as brain or body monitoring implants require high data rates to send data from the tag to the reader side. In most of the applications, the design of reader side is more relaxed compared to the tag side, due to the size and the power budget. Therefore, the tag side should be designed carefully and a proper communication scheme should be adopted to create an efficient remote powering system.

In order to achieve the specifications of the communication and also remote powering, the modulation method should be chosen carefully. The Frequency Shift Keying (FSK) method requires more bandwidth which decreases quality factors of the coils so the power transmission efficiency. Moreover, although the Phase Shift Keying (PSK) methods do not have impact on the quality factors of the coils, they require more complex circuits to modulate and demodulate the signal. Therefore, compared to FSK and PSK, the Amplitude Shift Keying (ASK) is commonly used in remotely powered systems. In this case, the signal is modulated by changing the amplitude of the signal. Besides, the ASK modulation and demodulation circuits are easy to be implemented and consume less power compared to other methods. In ASK modulation, the quality factors that are maximized for remote powering can be kept same depending on the necessary data rate. Thus, the power efficiency stays constant because the coil configuration does not change.

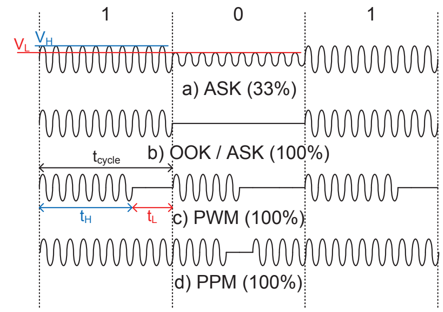


Fig. 2. Different encoding schemes modulated by ASK

In this paper, ASK communication with different digital encodings and different modulation depths is analyzed. Fig. 2 illustrates an example of different encoding schemes modulated by ASK.

In Fig. 2, V_H, and V_L, t_{cycle}, t_H, and t_L are the peak value of higher and the peak value of lower voltages, duration of sending one bit, duration of high voltage level and duration of low voltage level while sending one bit, respectively.

The ASK modulation is defined by modulation index (mi) which is given by mi = (V_H - V_L) / (V_H + V_L).

As seen in Fig. 2(a), the signal is modulated by ASK where mi equals to 33%. Fig. 2(b) shows the signal modulated by 100% of mi which is also called On-Off Keying (OOK) modulation. Fig. 2(c) and Fig. 2(d) present the signals modulated also by ASK however, encoded with Pulse Width Modulation (PWM) and Pulse Position Modulation (PPM), respectively. The difference between conventional ASK modulation and Pulse Modulation is detecting the time instead of amplitude. As seen from Fig. 2, in PWM, the bit "1" and the bit "0" are coded with the duration of the high voltage (t_H). Additionally, in PPM, the bit "0" is coded with the drop in the amplitude.

B. Communication Parameters (f_c, DR_{max}, D_{send}, BER)

In communication specifications, there are several performance metrics which are hard to be achieved at the same time. These parameters are: maximum data rate (DR_{max}), bit error rate (BER), amount of data which is needed to send (D_{send}) and the carrier frequency (f_c).

The operation frequency has a significant effect on increasing the bandwidth and consequently the maximum data rate. Besides, D_{send} and DR_{max} are also important features for communication. Furthermore, BER defines the error probability during the data transmission.

There is a clear trade-off between mi and BER. BER can be calculated for a certain peak amplitude and noise level by using the equations in [4]. Fig. 3 shows different BER curves obtained by using these equations for different modulation index values. As shown in Fig. 3, for a certain SNR value, the modulation index is limited to get required BER.

In some applications, the reader and tag can drift from their optimized position. This misalignment changes the coupling coefficient (k), which also determines the induced voltage as seen in Fig. 1 [5]. Therefore, the voltage will be varied,

$$pi = 0.5\left[\left(\frac{t_H(1+mi)^2 + t_L(1-mi)^2}{t_{cycle}(1+mi)^2}\right)_1 + \left(\frac{t_H(1+mi)^2 + t_L(1-mi)^2}{t_{cycle}(1+mi)^2}\right)_0\right] \tag{1}$$

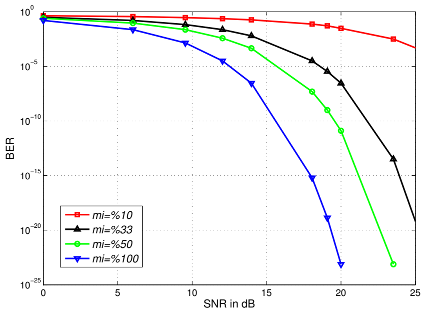


Fig. 3. BER vs. SNR plots for different mi values

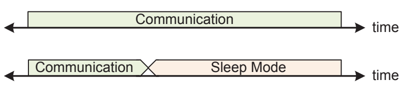


Fig. 4. Communication cycles for remotely powered systems

the noise level increases and this limits mi value in order to achieve a certain BER.

IV. Powering During Communication

A. Communication Rate (CR)

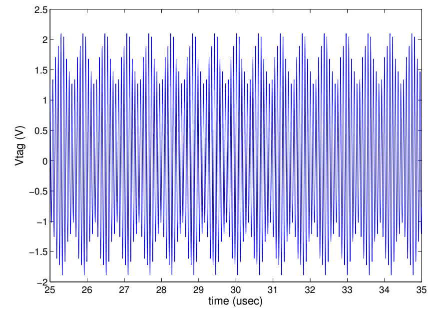
In each application there is a communication and computation cycle which repeats with a defined or undefined period which depends on the application. Assuming a system with necessary computation time is higher than communication cycle to have a more general perspective, there are two different communication cycle schemes as can be thought as seen in Fig. 4.

In first communication scheme, the system uses the entire cycle for data transmission, whereas in the second case, the communication is performed in a small portion of the one cycle and then the communication circuits go into sleep mode which decreases the total power consumption of the system. Therefore, the powering performance can be relaxed due to low-power consumption at the tag. This can be obtained by increasing DR_{max} for same D_{send} value.

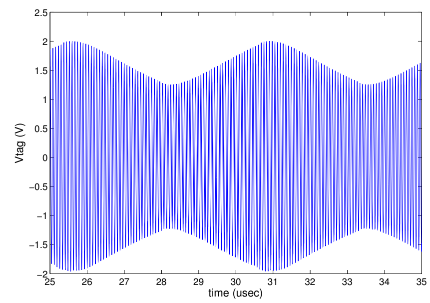
In order to calculate the portion of communication during one cycle, the communication rate (CR) is useful and it can be defined as $CR = D_{send} / DR_{max}$.

B. Modulation Rate (MR)

The modulation rate (MR) is related to number of peaks used in one bit duration to carry the information and the modulation rate is defined as $MR = DR_{max} / f_c$, where f_c is the carrier frequency. The modulation rate depends on the quality factors of the coils significantly [6]. In order to give an example and explain this, two ASK modulated signals



(a) Q = 6



(b) Q = 55

Fig. 5. Two ASK modulated signals with different quality factors

with different quality factors are given in Fig. 5. The signals have the same mi value. As seen from Fig. 5, higher quality factor requires more time to settle due to the lower bandwidth. Consequently, maximum achievable data rate is limited by quality factors of the coils. In addition, the data rate is also limited by the speed of the demodulator circuit.

C. Powering Index (pi)

As it was mentioned above, the remotely powered systems need power transfer to continue their operation. For a certain load impedance, the induced voltage at the tag depends on the voltage across reader coil (Fig. 1) and the change on the induced voltage also changes the transmitted power (P). Therefore, the amount of transmitted power during communication decreases (ASK) or can be even zero (OOK). In order to minimize the effect of the communication on powering performance, the modulation type should be chosen carefully. Hence, a powering index (pi) is defined to compare the modulation types in terms of their impact on powering performance in (1).

In (1), t_H, and t_L, t_{cycle}, and mi are the duration of high voltage level and low voltage level during one cycle, the duration of sending one bit, and modulation index, respectively. In the analysis it is assumed that the probability of sending bit

TABLE I
FoM V.S. D_{send} FOR DIFFERENT ENCODING SCHEMES

	Modulation Type				
	PPM [mi = 100%]	PWM [mi = 100%]	ASK [mi = 10%]	ASK [mi = 33%]	OOK [mi = 100%]
DR_{max}	[10, 0, 9, 1][1]	[8, 2, 4, 6]	[10, 0, 0, 10]	[10, 0, 0, 10]	[10, 0, 0, 10]
100 Kbit/s	0.1053 joule/bit	0.1667 joule/bit	0.1198 joule/bit	0.1595 joule/bit	0.2000 joule/bit
	[0.3, 0, 0.2, 0.1]	[0.2, 0.1, 0.1, 0.2]	[0.3, 0, 0, 0.3]	[0.3, 0, 0, 0.3]	[0.3, 0, 0, 0.3]
3.33 Mbit/s	$1.08 \cdot 10^{-4}$ joule/bit	$1.80 \cdot 10^{-4}$ joule/bit	$1.08 \cdot 10^{-4}$ joule/bit	$1.44 \cdot 10^{-4}$ joule/bit	$1.80 \cdot 10^{-4}$ joule/bit

[1]The vector arrays in the legend indicate the set of modulation parameters in the form of [t_{H1}, t_{L1}, t_{H0}, t_{L0}]. All dimensions are in μs.

"1" and bit "0" are equal to guarantee the data independency.

As an example, as seen from Fig. 2, if the communication system has ASK modulation with mi = 33%, the powering index can be calculated as 100% for bit "1" and as 25% for bit "0". This means that the system losses its 75% of P during sending bit "0". Therefore the average power transmission can be found as 62.5% of P during communication.

V. FIGURE–OF–MERIT

The introduced Figure-of-Merit (FoM) to compare the effect of communication on powering performance has two important parts; the first part presents the powering capability of the system and the second part emphasizes the communication factors and is given by;

$$FoM\left[\frac{joule}{bit}\right] = k_{pwr}k_{com} = \frac{P}{pi}\frac{CR}{MR(1-BER)} \quad (2)$$

In the first part, the overall power consumption of the remotely powered system (P) is the most important parameter. In addition, pi shows the impact of chosen modulation on the powering efficiency. In the second part, CR represents the duration dedicated to communication in one cycle. Besides, MR shows the speed to detect one bit that the communication circuits and channel can support. Finally, $(1 - BER)$ represents the probability of data transmission without error. Consequently, the remotely powered communication systems can be compared by using this FoM in terms of not only powering but also communication performances.

Table I shows examples for a certain remotely powered system with different modulation types. In both examples, the power consumption, the operation frequency and D_{send} are fixed to 1 mW, 10 MHz and 100 Kbit. Also, it is assumed that all the bits are received correctly (BER = 0%) during communication.

In Table I, the first example shows that a bit is coded with 100 periods of carrier frequency (t_{cycle} = 100/f_c). Therefore, the maximum data rate is 100 Kbit/s which is suitable for low-data rate applications. In the second example, a bit is coded with 3 periods of the carrier frequency (t_{cycle} = 3/f_c), hence the maximum data rate is 3.33 Mbit/s which is typical for high-data rate applications.

If the application does not require high-data rate, ASK modulation can be optimized to improve the powering performance by changing the encoding scheme. In the first example, OOK has the worst FoM value, i.e., 0.2 joule/bit for 100 Kbit data. Hence, in order to achieve better FoM, mi can be reduced or pulse modulation can be chosen. PPM has the best FoM value, i.e., 0.1053 joule/bit for 100 Kbit data.

In the same example, PWM is modified to improve FoM value, e.g., the time duration for detecting bit "1" and bit "0" are changed in order to improve the remote powering performance.

As observed from the second example, the duration of sending one bit becomes shorter when high-data rate communication is required. Therefore, the pulse modulations (PPM, PWM) which measure the durations become less efficient in terms of powering performance. As observed from the second example shows FoM values for the high-data rate required applications.

In conclusion, the trade-offs between remote powering and communication should be analyzed. Moreover, the modulation type should be chosen carefully for a specific remotely powered system.

VI. CONCLUSION

A Figure-of-Merit (FoM) is proposed to compare the different remotely powered communication systems. It consists of two parts. First part represents the powering capability parameters, i.e., overall power consumption of the system and powering index (pi). Second part expresses the communication properties, i.e., communication rate (CR), modulation rate (MR), and bit error rate (BER). The dimension of FoM function is joule/bit. In other words, it gives the required amount of energy to receive/transmit one bit correctly.

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